AD-A260 888

2

NAVAL POSTGRADUATE SCHOOL

Monterey, California

UNITED STATES NAVY • NAVAL POSTGRADUATE SCHOOL •

THESIS

MEASUREMENT OF SUB-MICRON
AL2O3
PARTICLES IN ROCKET PLUMES

by

John K. Vaughn

December, 1992

Thesis Advisor: David W. Netzer

Approved for public release; distribution is unlimited

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Naval Postgraduate School 6b. OFFICE SYMBOL *(If applicable)* 33	7a. NAME OF MONITORING ORGANIZATION Naval Postgraduate School
6c. ADDRESS *(City, State, and ZIP Code)* Monterey, CA 93943-5000	7b. ADDRESS *(City, State, and ZIP Code)* Monterey, CA 93943-5000
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Air Force Phillips Laboratory 8b. OFFICE SYMBOL *(If applicable)*	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS *(City, State, and ZIP Code)* *Edwards AFB, CA 9*	10. SOURCE OF FUNDING NUMBERS Program Element No. / Project No. / Task No. F04611-92-X-0327 / Work Unit Accession Number

11. TITLE *(Include Security Classification)*
MEASUREMENT OF SUBMICRON AL203 PARTICLES IN ROCKET PLUMES

12. PERSONAL AUTHOR(S) Vaughn, John

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT *(year, month, day)*	15. PAGE COUNT
Master's Thesis	From To	1992, December	54

16. SUPPLEMENTARY NOTATION
The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

17. COSATI CODES			18. SUBJECT TERMS *(continue on reverse if necessary and identify by block number)*
FIELD	GROUP	SUBGROUP	Solid-Propellant; Rocket Motor; Light Transmission; Particle Sizing

19. ABSTRACT *(continue on reverse if necessary and identify by block number)*

Transmission measurements using six wavelengths were made through the edges of plumes for solid propellant rocket motors using various propellants and motor geometries. The average values obtained for the aluminum oxide particles were a Sauter mean diameter of 0.30 +/- .02 microns, an index of refraction of 1.64 +/- .04 and standard deviation of 1.52 +/- .12 for the assumed monomodal, log-normal size distribution. The results indicated that the small aluminum oxide particles in the plume edge were gamma-AL203, independent of propellant composition, motor operating conditions and nozzle geometry. The good correlation of the data indicated that the small particles can be adequately represented by a monomodal, log-normal distribution.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS REPORT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION Unclassified	
22a. NAME OF RESPONSIBLE INDIVIDUAL Prof. David W. Netzer	22b. TELEPHONE *(Include Area code)* (408) 646-2980	22c. OFFICE SYMBOL Code AA/Nt

DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted. All other editions are obsolete. SECURITY CLASSIFICATION OF THIS PAGE

Approved for public release; distribution is unlimited.

Measurement of Sub-micron Al203 Particles in Rocket Plumes

by

John K. Vaughn
Captain, United States Army
B.S., United States Military Academy

Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN ENGINEERING SCIENCE

from the

NAVAL POSTGRADUATE SCHOOL
December, 1992

Author: John K. Vaughn

Approved by: David W. Netzer, Thesis Advisor

Raymond P. Shreeve, Second Reader

Daniel J. Collins, Chairman
Department of Aeronautics and Astronautics

ABSTRACT

Transmission measurements using six wavelengths were made through the edges of plumes for solid propellant rocket motors using various propellants and motor geometries. The average values obtained for the aluminum oxide particles were a Sauter mean diameter of 0.30+/-.02 microns, an index of refraction of 1.64+/-.04 and standard deviation of 1.52+/-.12 for the assumed monomodal, log-normal size distribution. The results indicated that the small aluminum oxide particles in the plume edge were gamma-Al_2O_3, independent of propellant composition, motor operating conditions and nozzle geometry. The good correlation of the data indicated that the small particles can be adequately represented by a monomodal, log-normal distribution.

TABLE OF CONTENTS

I. INTRODUCTION.....1

II. DIAGNOSTIC METHOD.....4

A. BACKGROUND.....4

B. THEORY.....4

III. EXPERIMENTAL APPARATUS.....9

A. ROCKET MOTOR.....9

B. LIGHT TRANSMITTING AND COLLECTION APPARATUS.....10

IV. DATA ACQUISITION AND REDUCTION.....14

V. RESULTS AND DISCUSSION.....16

A. DATA REDUCTION.....16

B. MEASUREMENT ACCURACY.....19

C. EFFECTS OF TEST CONDITIONS.....33

VI. CONCLUSIONS AND RECOMMENDATIONS.....35

APPENDIX A - SYSTEM UPGRADES.....37

APPENDIX B - HEWLETT PACKARD MULTIPROGRAMMER(HP6942A).....39

1. GENERAL DESCRIPTION.....39

2. 500KHZ A/D CARD(HP69759A).....40

3. HIGH SPEED MEMORY(HP69791A) AND MEMORY EXPANSION CARDS(HP69792A).....40

4. TIMER PACER CARD(HP69736A).....41

APPENDIX C - DATA ACQUISITION PROGRAM.....42

LIST OF REFERENCES.....45

INITIAL DISTRIBUTION LIST.....47

ACKNOWLEDGEMENTS

I would like to thank Prof. David W. Netzer for being a truly outstanding mentor. The tremendous learning experience and always pleasant working environment will never be forgotten. A special thanks also to Lab Tech. Harry Connor for his patience and great sense of humor.

Most of all, I especially thank my wife Maureen and children; their love, understanding, and unfailing support has been, and will always be, my inspiration.

I. INTRODUCTION

Aluminum is one of several metals that can be added to solid rocket propellants to increase the specific impulse. The addition of metals to the propellant, however, increases the exhaust signature of the plume. The particles in the plume are, in general, a result of the complete combustion of the aluminum [Ref. 1,2]. The particle size distribution throughout the exhaust nozzle and plume affects motor performance, plume visibility, infrared signature, and the environment [Ref. 3,4]. The particle size distribution and particle optical properties vary throughout the plume. Plume flowfield models, such as SPF, and plume radiation models, like SIRRM, are used to predict the plume signature, however none of the models have been adequately validated [Ref. 5,6].

Two commonly used methods to analyze particles within the plume are sample withdrawal, and in situ optical measurements. In the sample withdrawal procedure, particles are collected on a filter or solid surface, or they are removed through a tube for analysis. The optical techniques measure the transmission or the scattering of light that is directed through the plume. The later techniques have the advantage of providing continuous measurements without disturbing the flowfield.[Ref. 7]

Highly aluminized propellants produce plumes containing large amounts of aluminum oxide. Particles in the outer edges of the plume can then dominate the plume signature. Small particles (micron, submicron) dominate in this outer plume region because the larger particles cannot turn with the gas flow through the nozzle throat and follow the wall profile. Thus, the optical properties and size of the small particles are important for plume signature prediction.[Ref. 2]

Diagnostic techniques used for determining particle size and optical properties generally have limited dynamic ranges. Techniques that work for submicron particles generally do not work for large particles, and visa-versa. One technique that has been successfully used for submicron particles is multiple-wavelength light transmission measurements [Ref. 3,7]. These measurements are sometimes augmented by light scattering measurements [Ref. 4,8].

In a recent investigation at the Naval Postgraduate School, the multiple-wavelength technique was used to measure the particles in the edges of the plume of a small solid propellant rocket motor. It was found that the particles in this region were dominated by small particles which had an index of refraction of $1.63 \pm 8\%$, and a Sauter mean diameter of $0.15\mu \pm 4\%$. Recommended improvements to that investigation were to significantly increase the rate of data acquisition and incorporate additional wavelengths, to reduce the effects of time-variation in motor

operating conditions, and to provide more data for improved accuracy of the technique.[Ref. 9]

Since the small particles in the edges of the plume can dominate the plume signature, it is desirable to know whether or not their size and optical properties are somewhat "universal" or whether they vary significantly with propellant composition, motor geometry, and /or motor operating conditions. The work of Kim [Ref. 9] concentrated on the development of the diagnostic technique, resulting in only very little data being obtained.

The purposes of this investigation were (1) to improve the diagnostic method utilized by Kim [Ref. 9] by significantly increasing the rate of acquisition of data and by increasing the number of wavelengths employed and (2) to apply the improved system to a wider range of test conditions to determine the effects on particle size and optical properties.

II. DIAGNOSTIC METHOD

A. BACKGROUND

The optical analysis of particles dates back to Lord Rayleigh and the nineteenth century. Rayleigh's theory explained the scattering of light from particles whose dimensions were a great deal smaller than the actual wavelength of the light. Additionally this allowed him to explain the blue sky in terms of the small particles suspended in the upper atmosphere. (The more general technique used to measure all particles sizes is the Mie theory.) [Ref. 4,8]

Since Rayleigh's initial discoveries, lasers and computers have significantly refined the optical process, but the fundamental approach is still the same. A collimated light beam is sent through a particle cloud and information about the particles is determined based upon the wavelength dependence of the scattering and extinction of the light beam [Ref. 4]. Extinction in this case, refers to the reduction in intensity of the light due to absorption and scattering of the incident light by the particles.

B. THEORY

The Bouguer or Beer-Lambert law [Ref. 3,7], describes the exponential decay of the intensity of a light beam as it passes through a particle field of uniform size:

$$T = \exp(-QAnL) = \exp(-\frac{3QC_mL}{2\rho d}) \qquad (1)$$

where T = fraction of light transmitted,

Q = dimensionless extinction coefficient,

A = cross sectional area of a particle,

n = number concentration of particles,

L = path length,

C_m =mass concentration of particles

ρ = density of and individual particle

d = particle diameter

Mie scattering theory explains the interaction of a plane electromagnetic wave with a spherical object, and allows computation of Q as a function of particle size, wavelength of light, and complex index of refraction of the particle. Since Mie's initial discoveries, further extensions of his theory have been made, making it applicable to nonspherical particles as well. The theory holds for nonspherical particles if they are approximated by spherical particles whose diameters give them the same volume as the nonspherical particles. [Ref. 3,7]

Dobbins [discussed in Ref. 7] revised Bouguer's transmission law for a polydisperse system of particles:

$$T = \exp\left(-\frac{3\bar{Q}C_m L}{2\ \rho d_{32}}\right) \qquad (2)$$

where $\bar{Q}$ is the average extinction coefficient, and d_{32} is the volume-to-surface (Sauter) mean particle diameter. Taking the natural logarithm of equation (2) yields:

$$\ln T = \bar{Q}\left(-\frac{3C_m L}{2\ \rho d_{32}}\right) \qquad (3)$$

Since the light beam has identical path lengths, ρ, C_m, and d_{32} for each wavelength through the exhaust plume, the ratio of the ln-transmissions at any two wavelengths is equal to the ratio of the calculated extinction coefficients for the same wavelengths:

$$\left.\frac{\ln T(\lambda_i)}{\ln T(\lambda_j)}\right|_{experimental} = \left.\frac{\bar{Q}(\lambda_i d_{32})}{\bar{Q}(\lambda_j, d_{32})}\right|_{theoretical} \qquad (4)$$

A computer code [Ref. 7], utilizing Mie theory, was used to generate the values for $\bar{Q}$.

The transmittances at each of the various wavelengths are determined experimentally. The procedure requires calculations of $\overline{Q}$ for various values of λ, d_{32}, m(=n-ik), and an assumed particle size distribution. If the chosen values are correct, calculated extinction coefficient ratios will match the measured ln transmission ratios for each of the wavelengths utilized. Studies have shown little variation in the measured indices of refraction with wavelengths in the visible and near infrared ranges; thus, for the Mie calculations, the indices were assumed constant [Ref. 7].

Depending upon the assumed shape of the size distribution (monomodal, bi-modal, log normal, upper-limit,etc.), one or more parameters are required to characterize it. Based upon the studies of Chippett and Gray [discussed in Ref. 7], small particles in plumes often have a monomodal log-normal distribution. In this case the distribution is specified by d_{32} and the standard deviation(σ). If the distribution is log-normal and the particles are absorbing (complex refractive index) then there are four unknowns; n,k,d_{32}, and σ, requiring a minimum of four independent measurements involving these parameters.

Calculations with the Mie code showed an insensitivity to the absorption index for the reported values for aluminum oxide($<10^{-3}$); so for the calculations, the absorption index of the Al_2O_3 particles was assumed to be zero [Ref. 9]. With three unknown variables(d_{32},σ, and n (or m)), a minimum of three independent ln-transmission ratios were needed. The actual

technique utilizes many more ln-transmission ratios. The values of n, d_{32}, and σ, are found by regression analysis, i.e. finding the best agreement between the measured and calculated results. Increasing the number of wavelengths, increases the confidence level in the data correlation.

III. EXPERIMENTAL APPARATUS

A. ROCKET MOTOR

The rocket motor used in this experiment was the same one used by Kim[Ref. 9]. The external dimensions of the motor were approximately 10.5" in length by 3.25" in diameter. The motor consisted of an ignitor, nozzle, burst disk, pressure transducer, main body and end covers. These components are shown in figure 1.

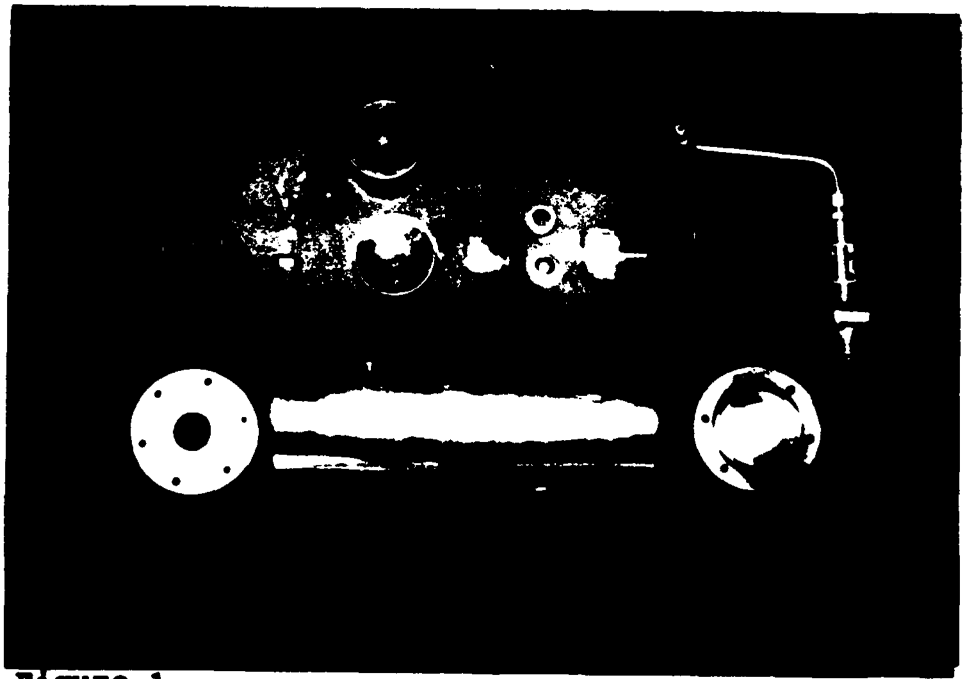


Figure 1
Motor components

The Air Force Phillips Laboratory provided a GAP/AP propellant containing 4.7% aluminum for use in the motor. Morton Thiokol

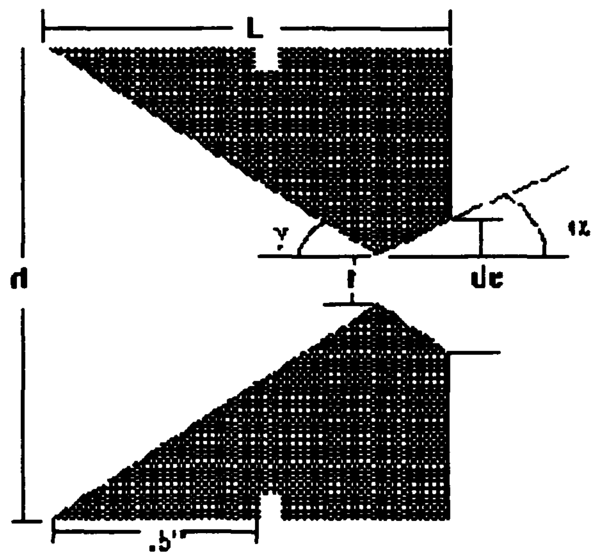
provided an HTPB/AP propellant with 16% aluminum. The propellants were cut to burn either radially (with a 2" outside diameter, a .375"web and a length of 1-2") or axially(2" outside diameter and a length of 1-1.5"). The portion of the motor walls to be in contact with the propellant surface were lightly coated with 732-RTV self-vulcanizing silicone, in order to hold the propellant in place, and to act as an burning inhibitor. To ignite the motor, a voltage provided by a 12V battery was applied to a $BKNO_3$ ignitor.

To prevent possible overpressurization of the motor during firing, a disposable 1500 psi burst disk was installed on the side of the motor wall. To record motor pressure, a pressure port for a pressure transducer was placed in the combustion chamber[Ref. 9]. The nozzle specifications are shown in TABLE 1.

B. LIGHT TRANSMITTING AND COLLECTION APPARATUS

The light source for the experiment consisted of an Oriel Mercury-Xeon white light(Model 66085, with peak wavelengths at 253.4, 302.2, 312.6, 334.2, 366.3, 404.7, 435.8, 546.1, and 577.0nm) A collimated white light was transmitted through the plume and onto an Oriel Model 77400 Multispec spectrograph through a 25μm wide slit. The small slit width was necessary to insure that the amount of scattered light received by the detector was insignificant in comparison to the total amount of light that penetrated through the slit. [Ref. 10] The light was then

TABLE 1 NOZZLE SPECIFICATIONS



	Description	Nozzle #1	Nozzle #2
1	Outside Diameter(d)	2.12"	2.12"
2	Length(L)	1.24"	1.9"
3	Throat Diameter(t)	.217"	.265"
4	Exit Diameter(d_e)	.381"	.811"
5	Converging half-angle(γ)	45.0°	45.0°
6	Diverging half-angle(α)	15.0°	15.0°

reflected from a mirror to a diffraction grating. The light was then reflected off of another mirror to a 1024 element diode array [Ref. 11]. A schematic of the optical pattern is shown in Figure 2.

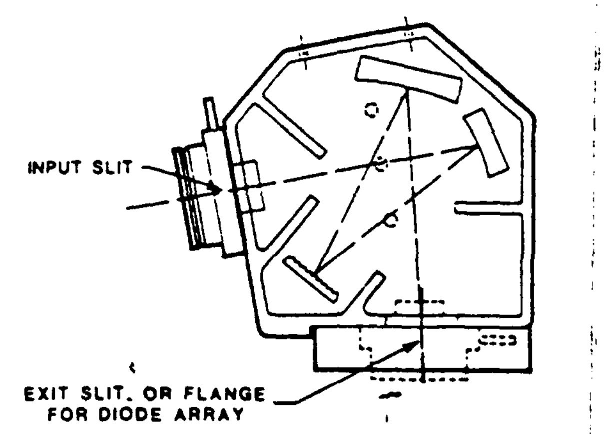


Figure 2
Spectrograph Optical Pattern
[Ref. 10]

The response characteristic of the photodiode area is shown in fig 3. With these response characteristics, six of the ten available wavelengths could be detected (334.2, 366.3, 404.7, 435.8, 546.1, 577.0nm)[Ref.11].

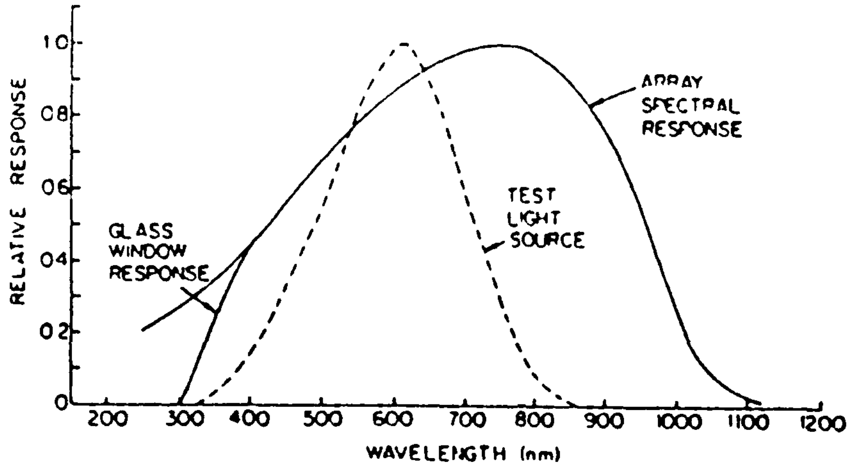


Figure 3
Diode Response Char.
[Ref. 11]

IV. DATA ACQUISITION AND REDUCTION

The output of the diode array was sent to a HP6942A Multiprogrammer, where the analog signal was converted to digital, and stored on high speed memory cards. Collection and storage of the data was controlled by using a HP9836S Computer. The timing circuit of the diode array board was synchronized with the Multiprogrammer. The Multiprogrammer system consisted of:

1	500Khz Analog to Digital Converter Card
1	High Speed Memory Card
4	Memory Expansion Cards
1	Timer Pacer Card

The A/D card was configured for external triggering, allowing the timer pacer card to control the rate of conversion. The timer pacer card was also configured for external triggering, allowing it to be paced by the blanking pulse from the diode array board. With this control, data were collected at the beginning of each sweep of the array, without large gaps in data between sweeps. A timing diagram is shown in figure 4.

The data from the sweeps were stored in binary data files(BDAT). Each BDAT contained data from eight sweeps of the 1024 element diode array(8096 bytes). There were six peak voltages in each sweep, corresponding to each of the wavelengths.

During a single test four sequential BDAT files were used, giving a total of 32 sweeps of the diode array. Several programs were written [and adapted from Ref. 12]to aid in finding the peaks and to determine if any of the sweeps contained bad data. The peak voltages were averaged according to wavelength for both particle and no particle data. The transmittances were determined by taking the ratio of particle to no particle data for each wavelength.

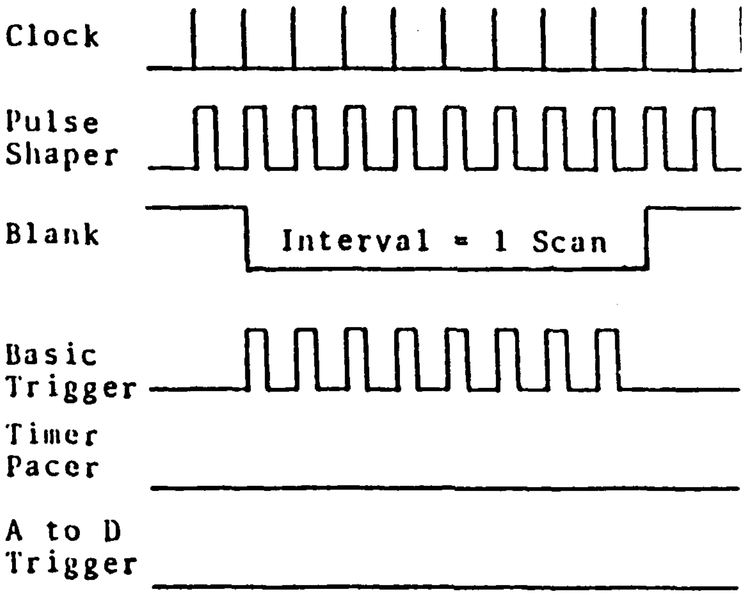


Figure 4
Timing Diagram

V. RESULTS AND DISCUSSION

A summary of the propellants, nozzle sizes, operating pressures, and data collection locations for each run is shown in TABLE 2. Various nozzle geometries were used to provide different chamber pressures and different degrees of over-and under-expansion.

A. DATA REDUCTION

The index of refraction of the Al_2O_3 particles in the plume was assumed to be independent of wavelength, and the absorption index was taken to be zero for the reasons discussed above. Q was determined as a function of d_{32}, n, and σ using the Mie code. The ratio of mean extinction coefficients were then plotted against the ln-transmission ratios for each pair of wavelengths, for a total of fifteen ratios. If the ratios had corresponded with each other perfectly, the data points would have formed a forty-five degree line passing through the origin. Short of this, the best fit of data would have the least scatter about this line, and would form a line with a slope approximately equal to one.

Finding the correct combination of d_{32}, σ, and n was an iterative process that began with expected values taken from Kim's report [Ref. 9]. A linear least-squares fit method was used to find the correlation coefficient, R, as a measure of the relationship between the ln-transmission ratios and the extinction coefficient ratios. The square of the correlation coefficient

expressed as a percentage was used to measure how closely the data points matched the regression line. The R^2 value closest to one indicated the best linear correlation between the data. The X-Coefficient (slope) of the regression analysis, indicated how closely the slope of the least-squares fit matched a 45° line.[Ref. 13:p. 17]

TABLE 2. TESTS CONDUCTED

Test #	% AL GC GL (in.)	d_{th} (in.)	d_e (in.)	P_c (psia)	P_e (psia)	PL $x(x/d_e)$ $r(r/r_e)$ (in.)
1	16% rad 2	.265	.811	780	10.9 slightly over-expanded	6(7.4) 1.4(3.5)
2	16% rad 1.5	.265	.811	405	5.5 over-expanded	6.5(8.0) 1.4(3.5)
3	4.69% end 1	.217	.381	630	42.3 under-expanded	6(15.7) 1.2(6.3)
4	4.69% end 1	.265	.811	195	2.7 highly over-expanded	6(7.4) 1.2(3.0)

end - end burning grain

GC - grain configuration

GL - grain length

rad - radial burning grain

PL - plume location aft of nozzle exit

B. MEASUREMENT ACCURACY

Earlier studies conducted by Kim [Ref. 9] using the multiple wavelength transmittance apparatus had determined the approximate experimental measurement accuracy of the transmittances (due to electronic noise) to be within 0.5%. When wavelengths are closely spaced and or higher transmittances (above 90%) occur, this accuracy results in a large uncertainty in the ln-transmission ratio. To reduce the effects of this problem and increase the confidence in the measurement accuracy, the number of wavelength ratios was increased. The larger number of closely spaced data points reduce the possibility of fitting several regression lines through the same data. In addition, the higher speed data acquisition permitted 32 sweeps of the diode array in 70msec. This significantly increased the number of repeated measurements for averaging and decreased the total sampling time from that utilized by Kim [Ref. 9]. The latter results in less variation due to changing motor conditions during the measurement sequence. When the best solution was found using fifteen wavelength ratios, d_{32}, σ, and n were perturbed about their nominal values until a 2% variation in slope (X-coefficient) was noted in the plotted solution. The graphical results of these perturbations are shown in Figures 6 through 17. From this analysis, for a 2% variation in X-Coefficient, the accuracy of the measured values of d_{32}, n, and σ were estimated. A summary of these results is shown in Table 3. The resulting average uncertainty in d_{32} and σ were

slightly increased from that determined by Kim. However, the uncertainty in the index of refraction was significantly reduced. The good correlation of the data indicated that the particle size distribution could be satisfactorily represented by a log-normal distribution.

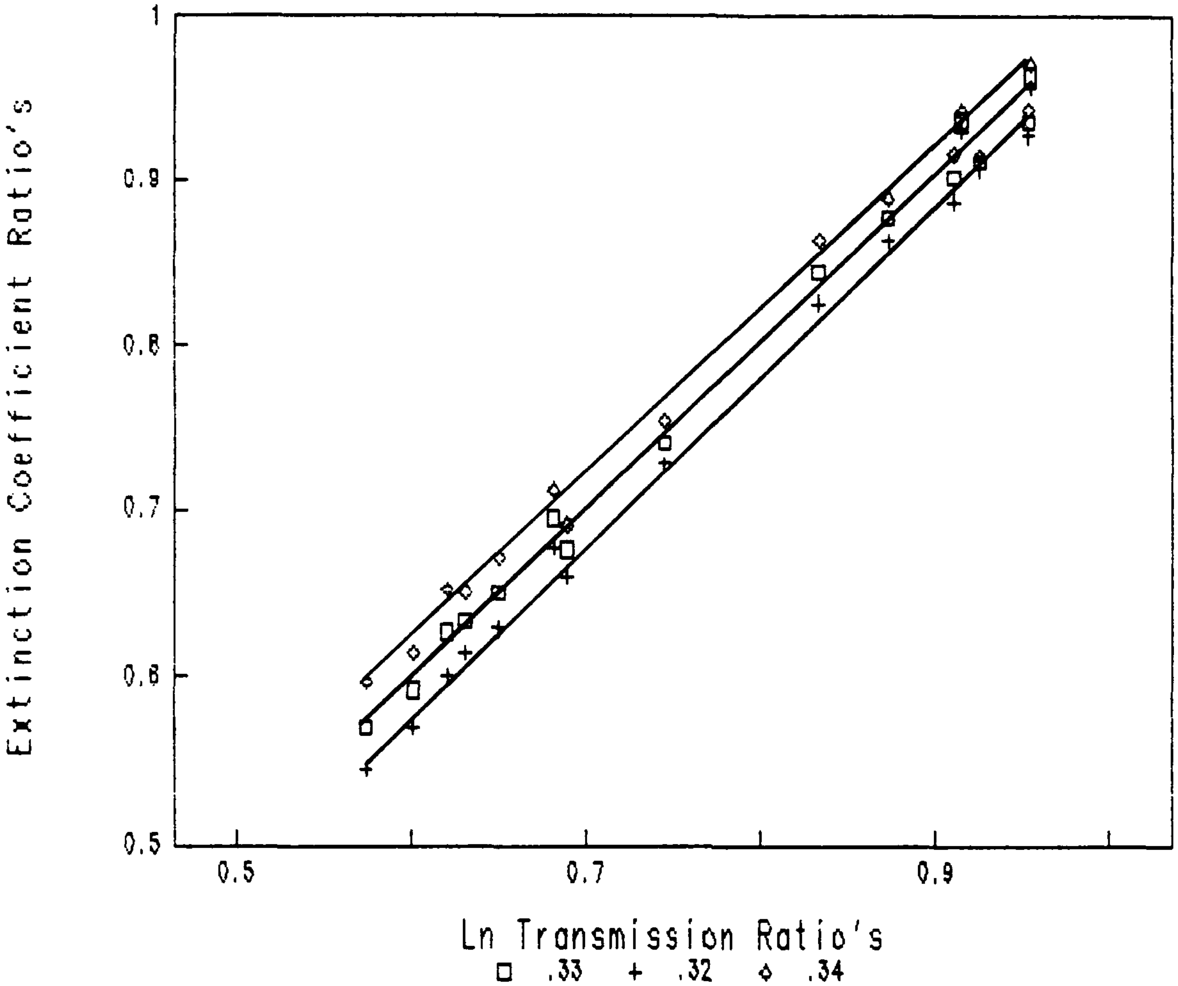


Figure 6.
Results of Perturbation of d_{32} about .33,Run 1

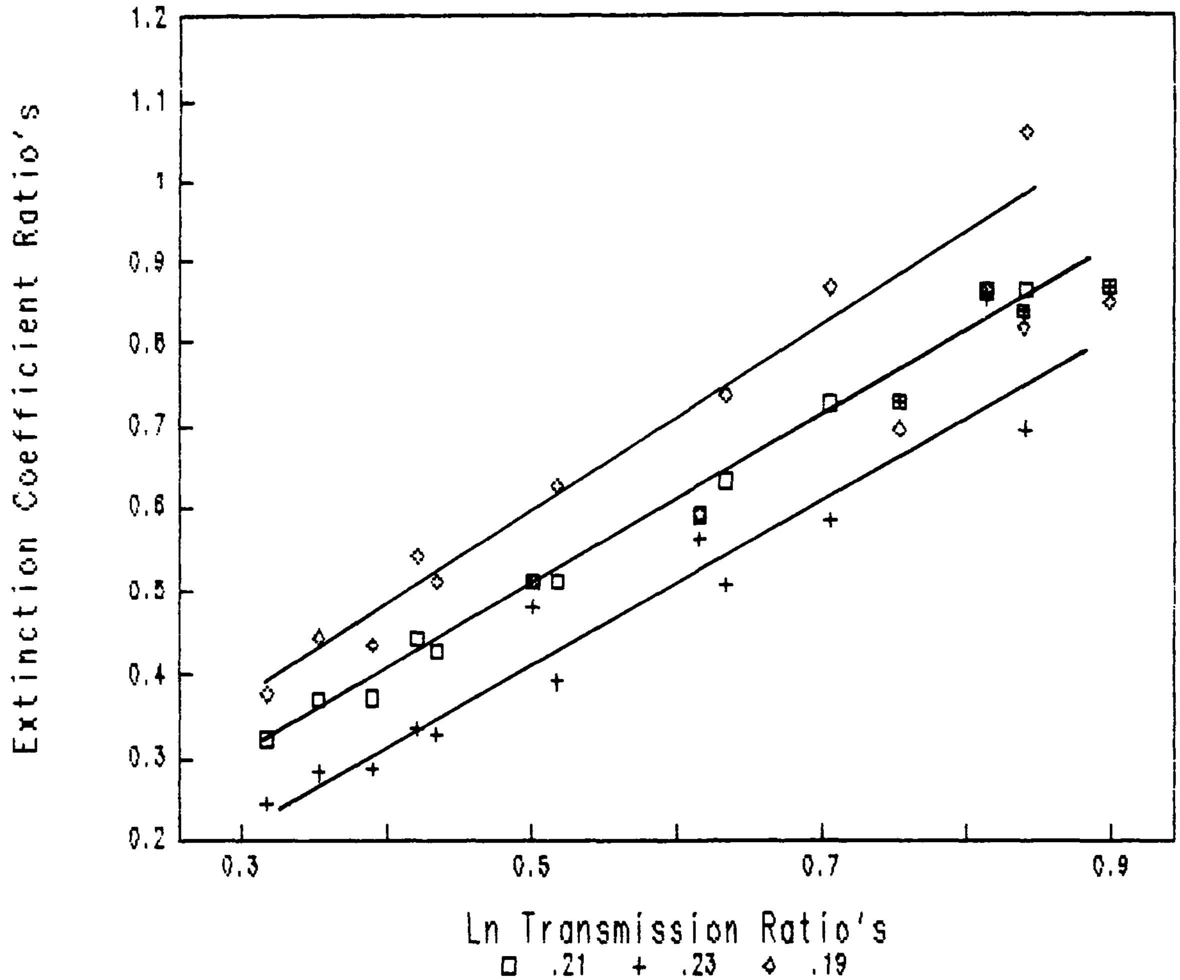


Figure 7.
Results of Perturbation of d_{32} about .21,Run 2

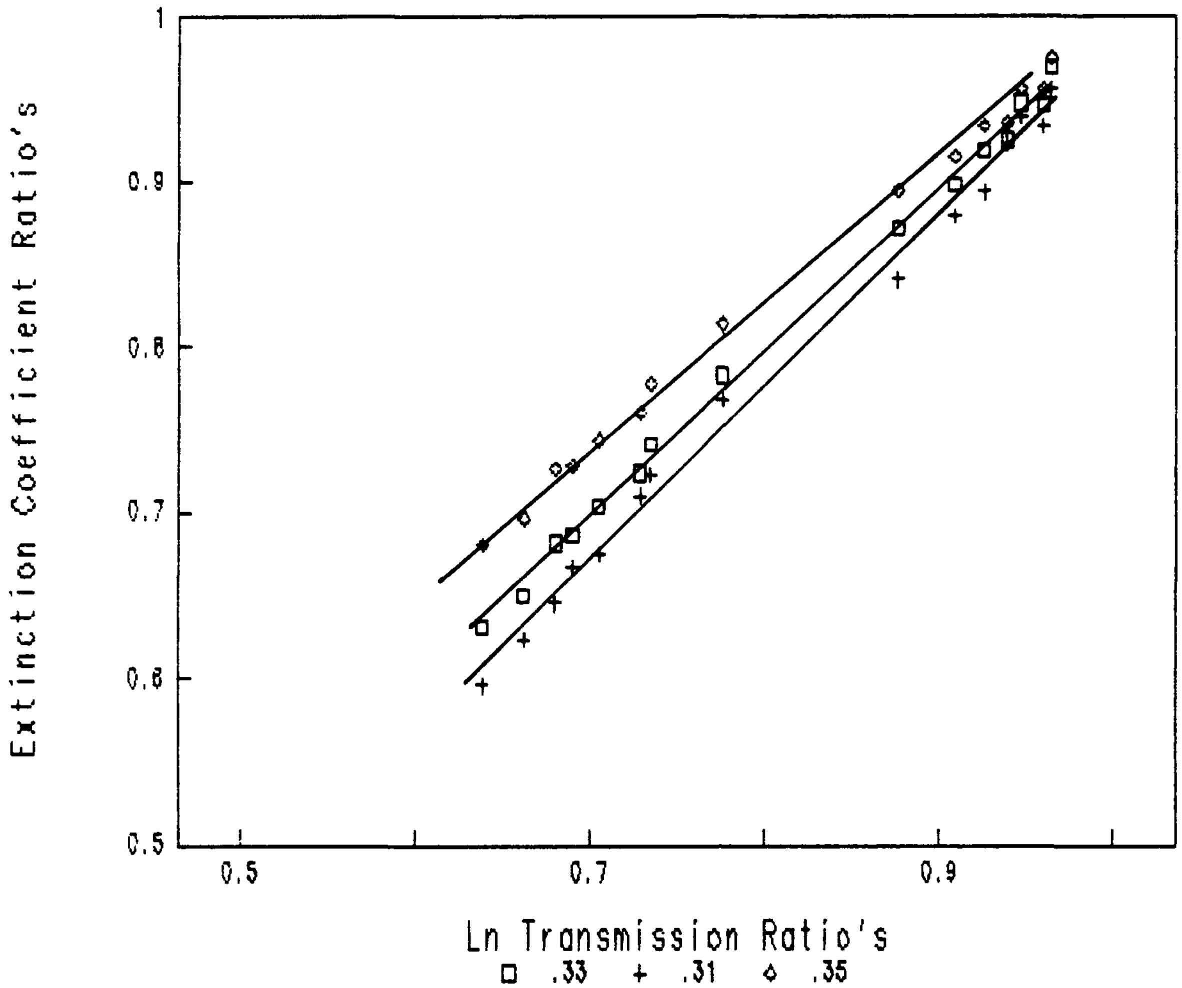


Figure 8.
Results of Perturbation of d_{32} about .33,Run 3

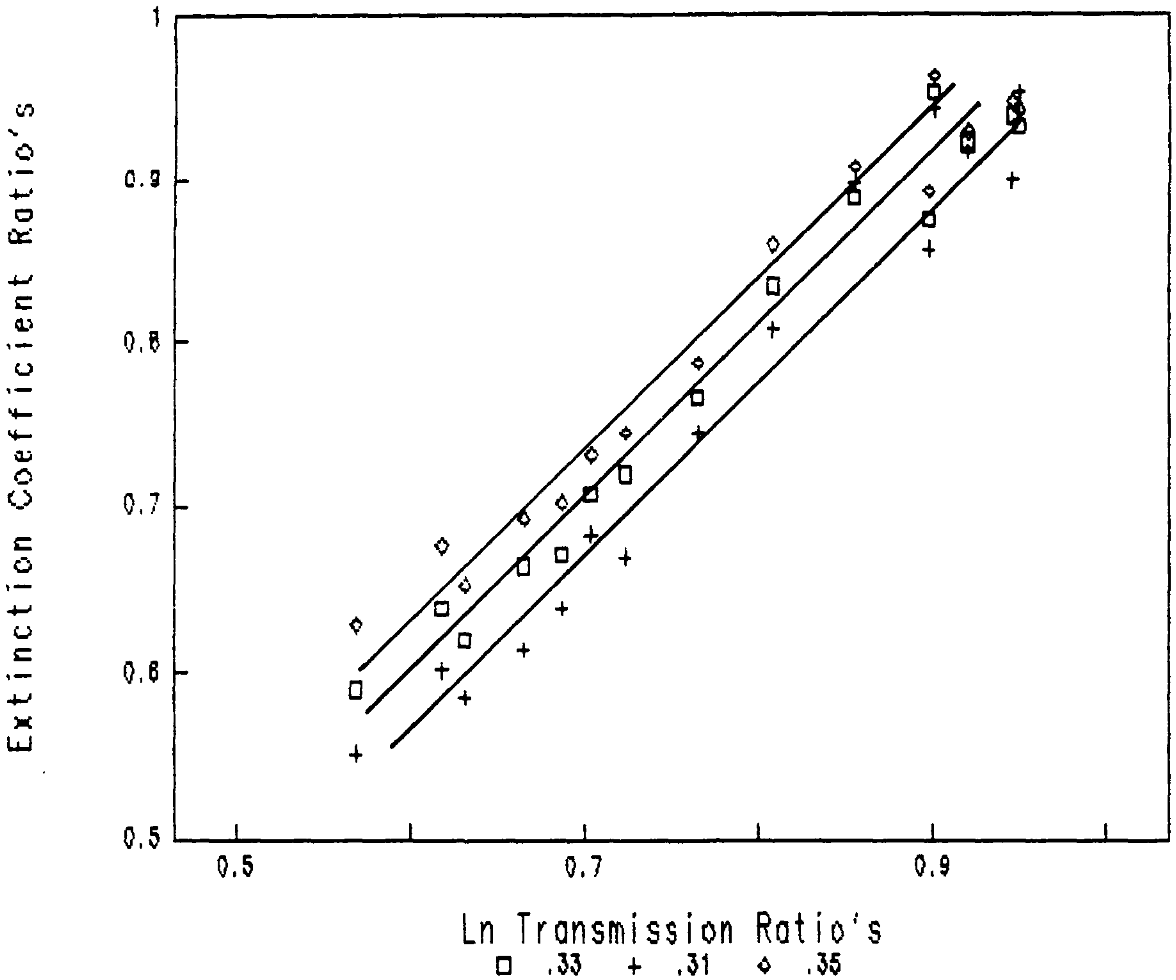


Figure 9.
Results of Perturbation of d_{32} about .33, Run 4

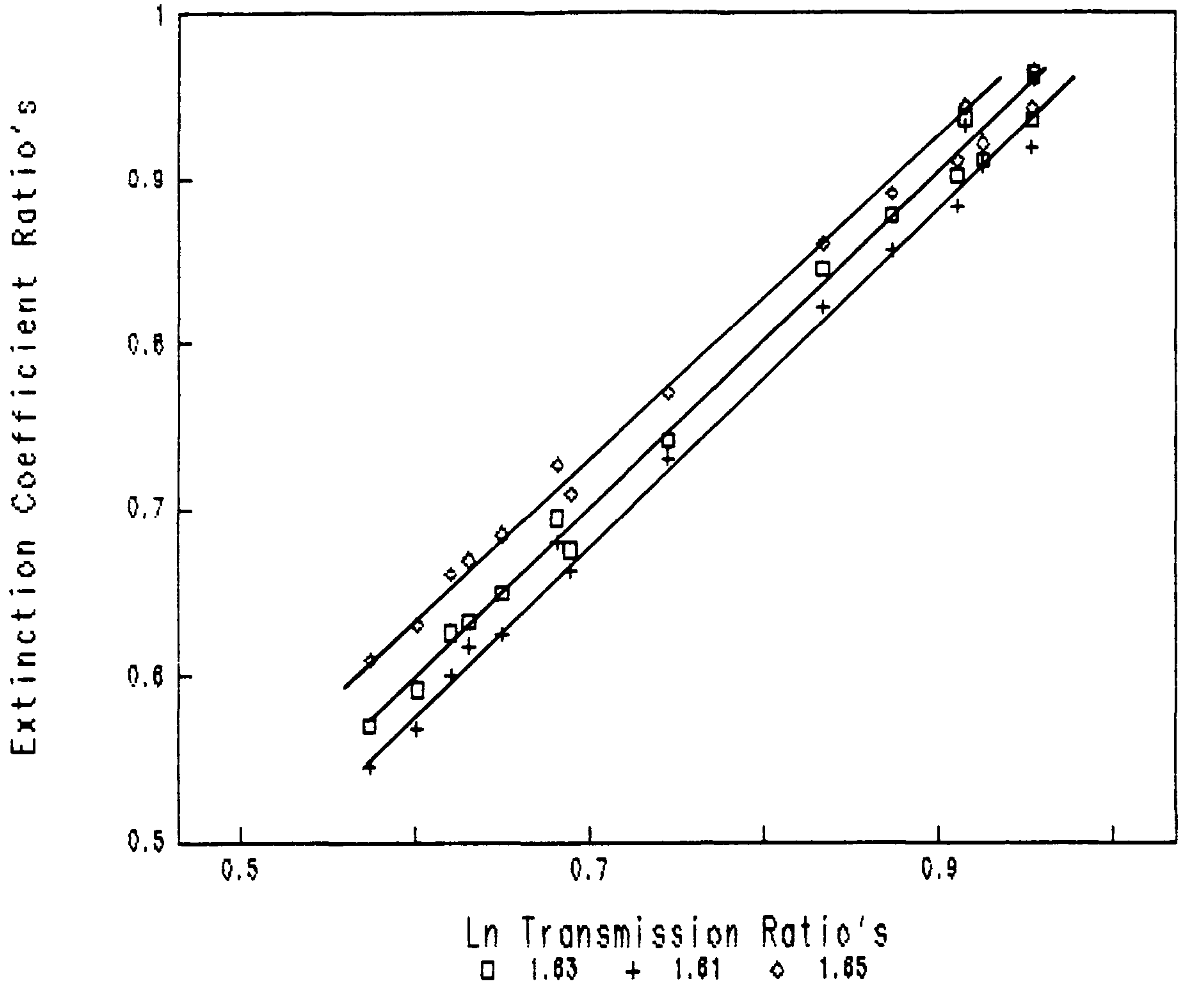


Figure 10.
Results of Perturbation of n about 1.63,Run 1

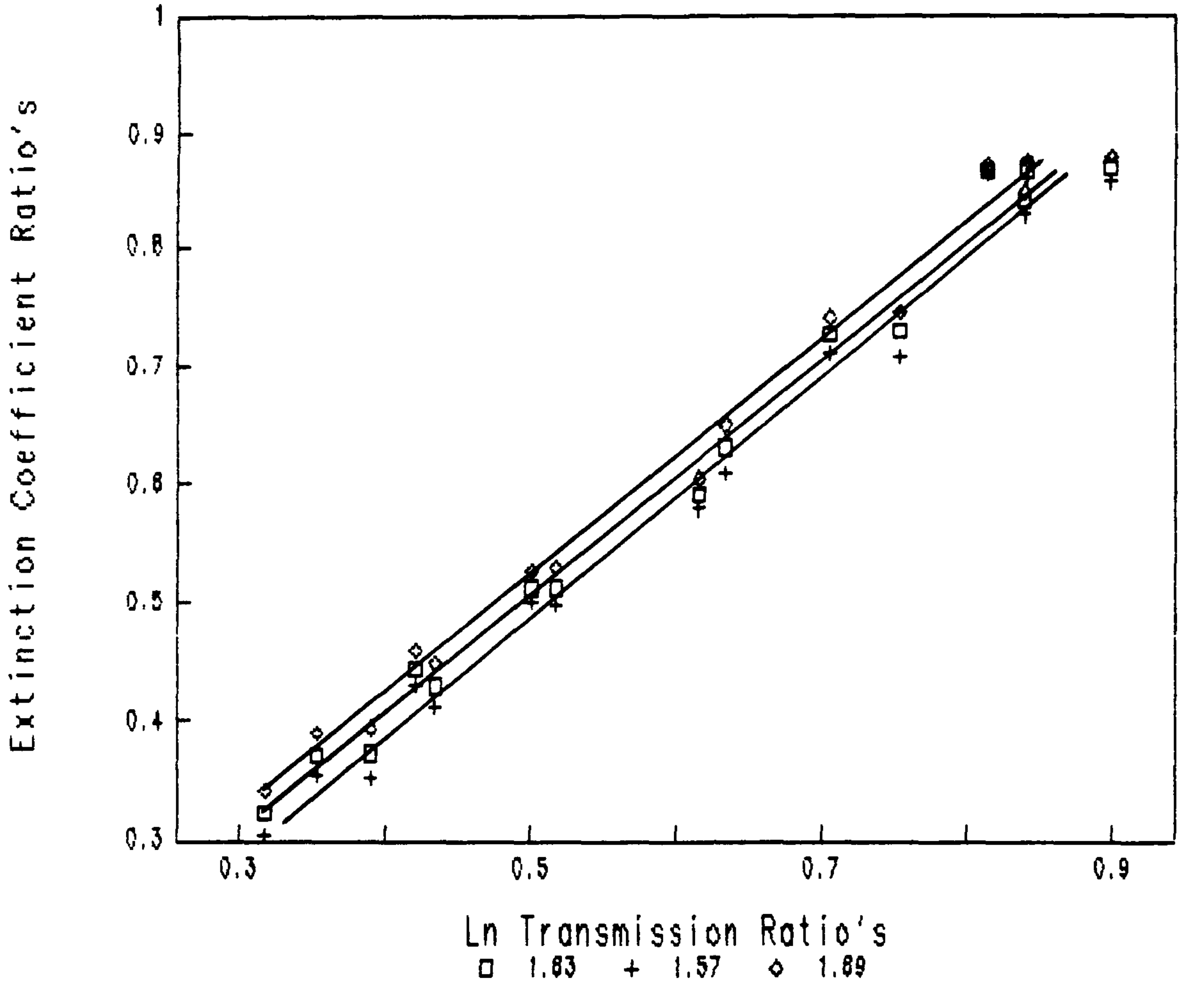


Figure 11.
Results of Perturbation of n about 1.63,Run 2

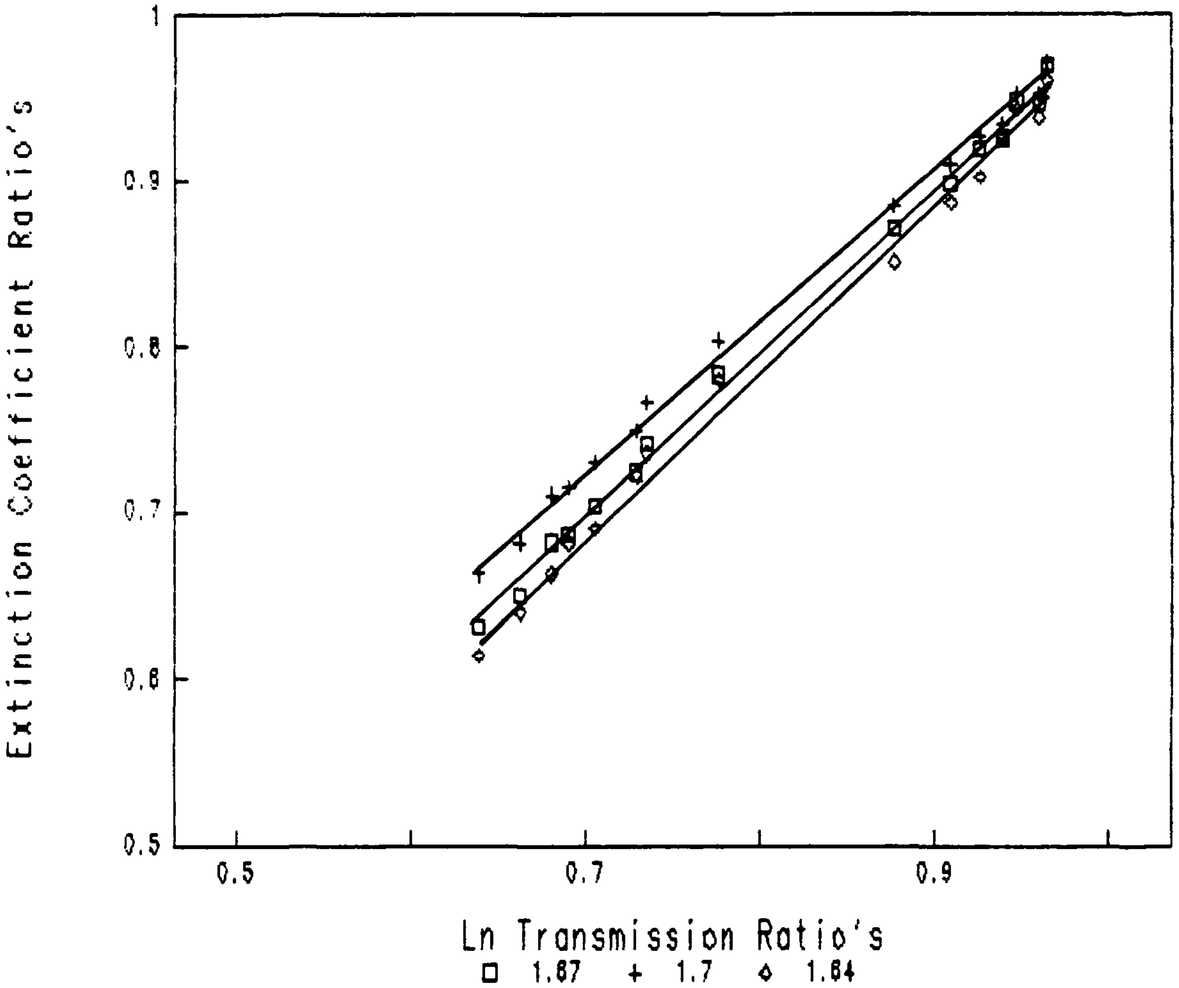


Figure 12.
Results of Perturbation of n about 1.67,Run 3

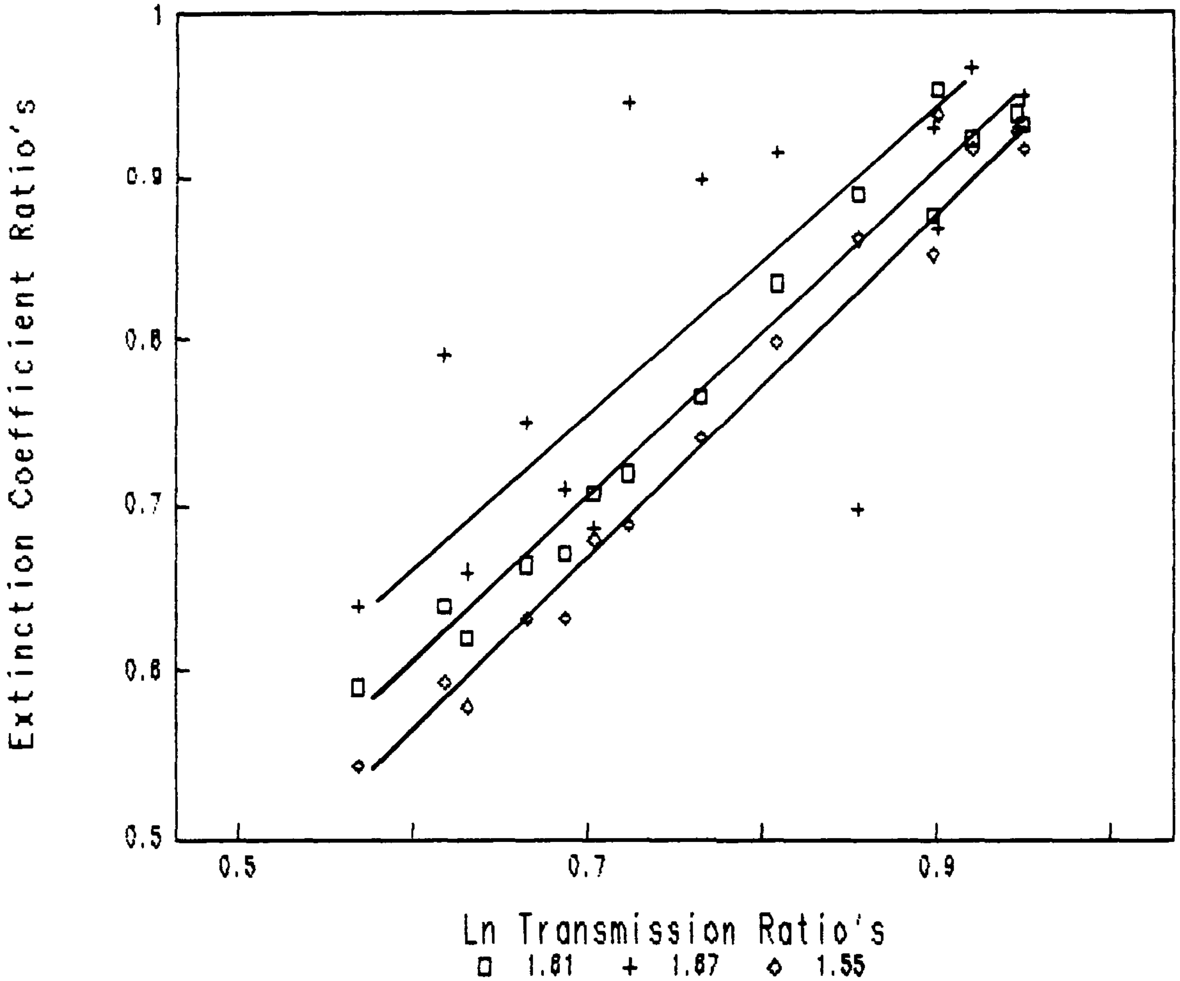


Figure 13.
Results of Perturbation of n about 1.61,Run 4

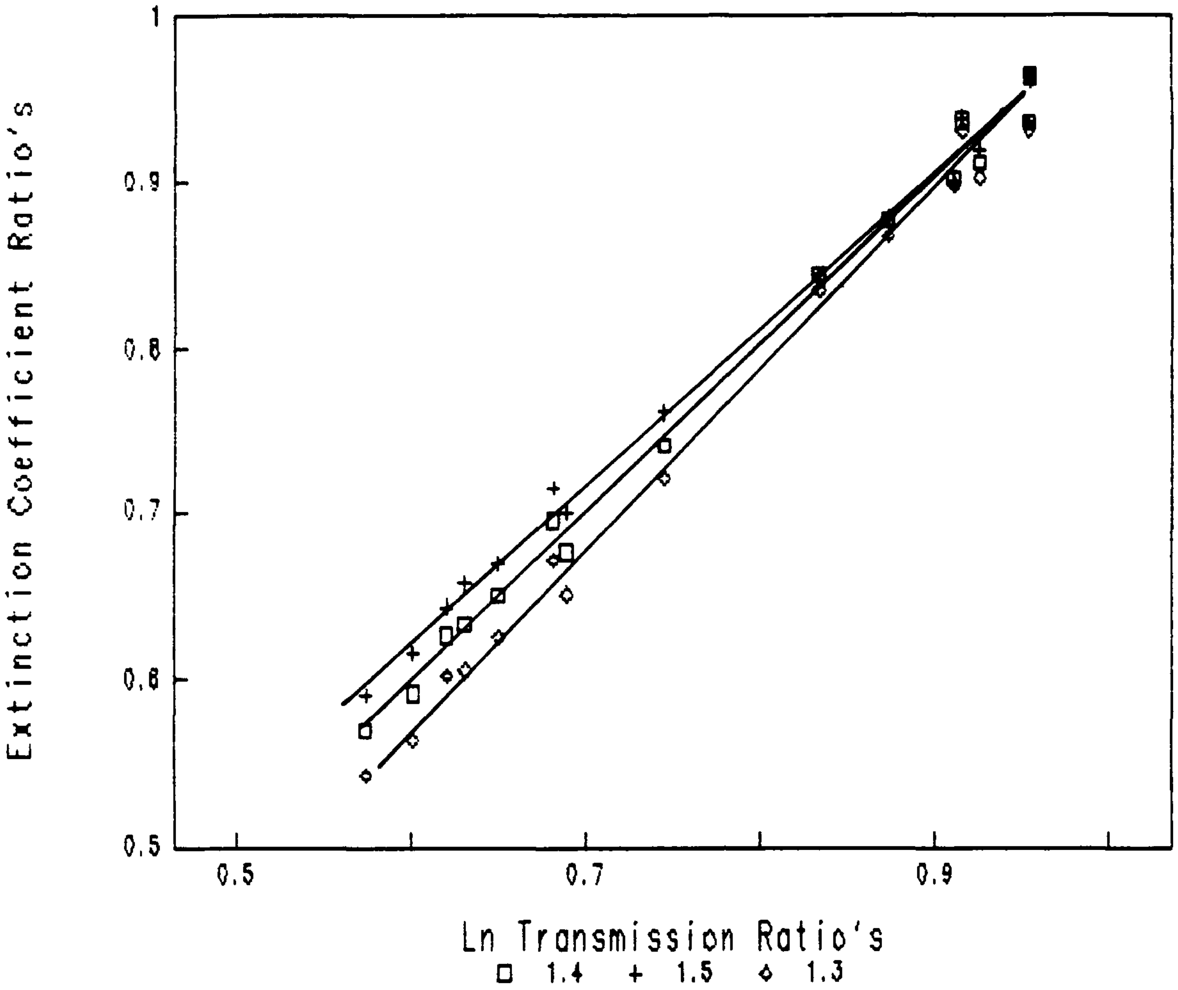


Figure 14.
Results of Perturbation of sigma about 1.4,Run 1

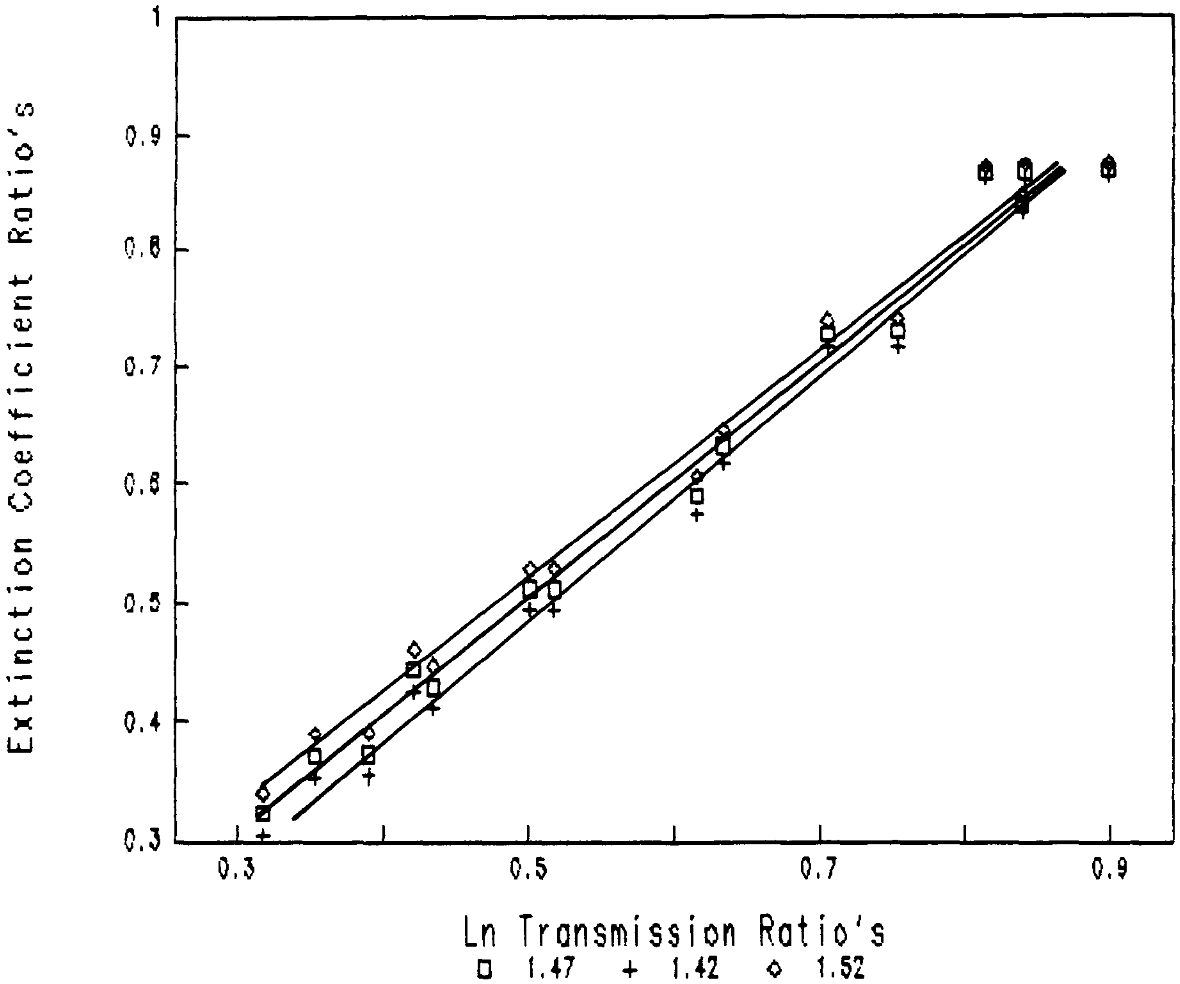


Figure 15.
Results of Perturbation of sigma about 1.47,Run 2

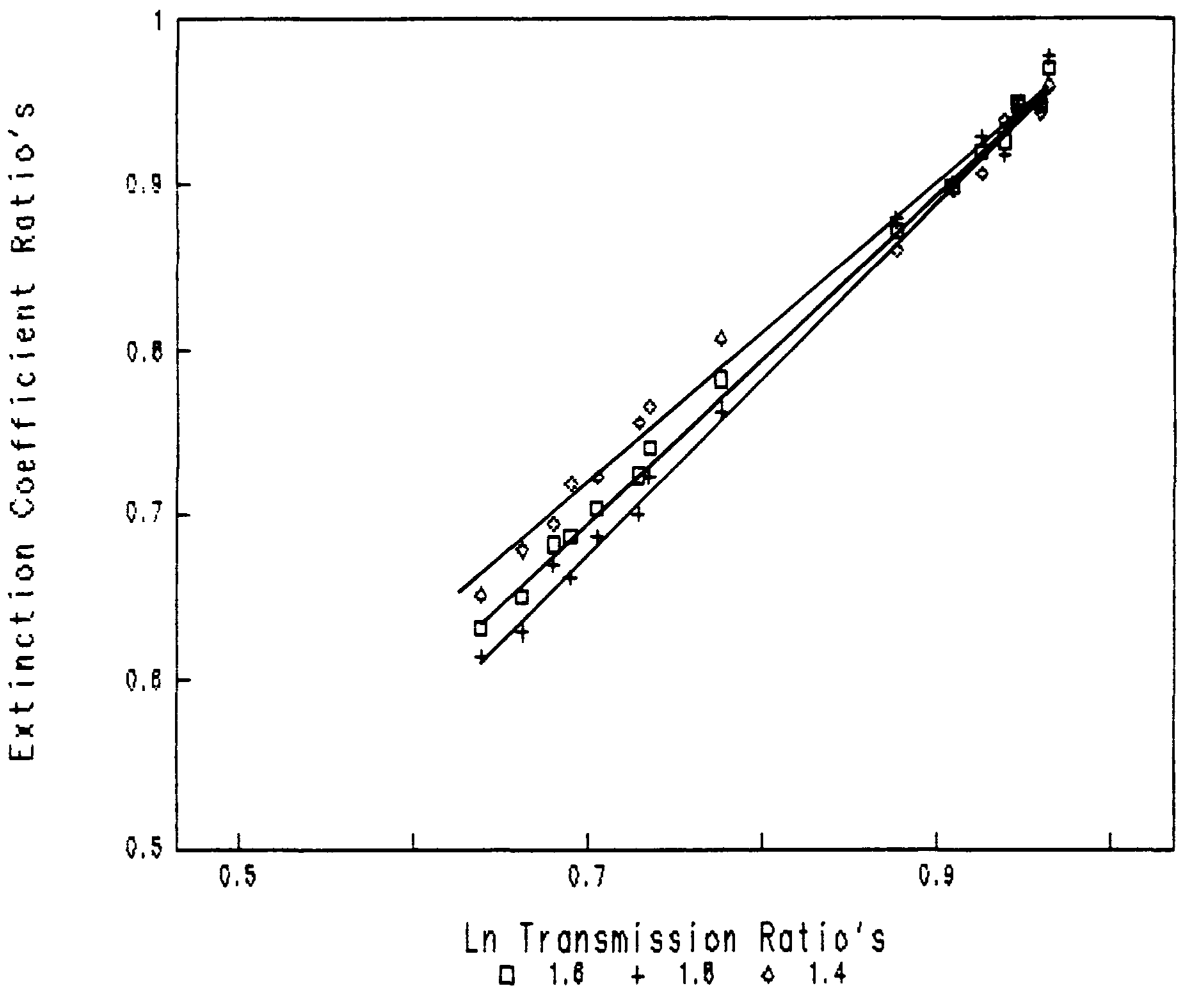


Figure 16.
Results of Perturbation of sigma about 1.6,Run 3

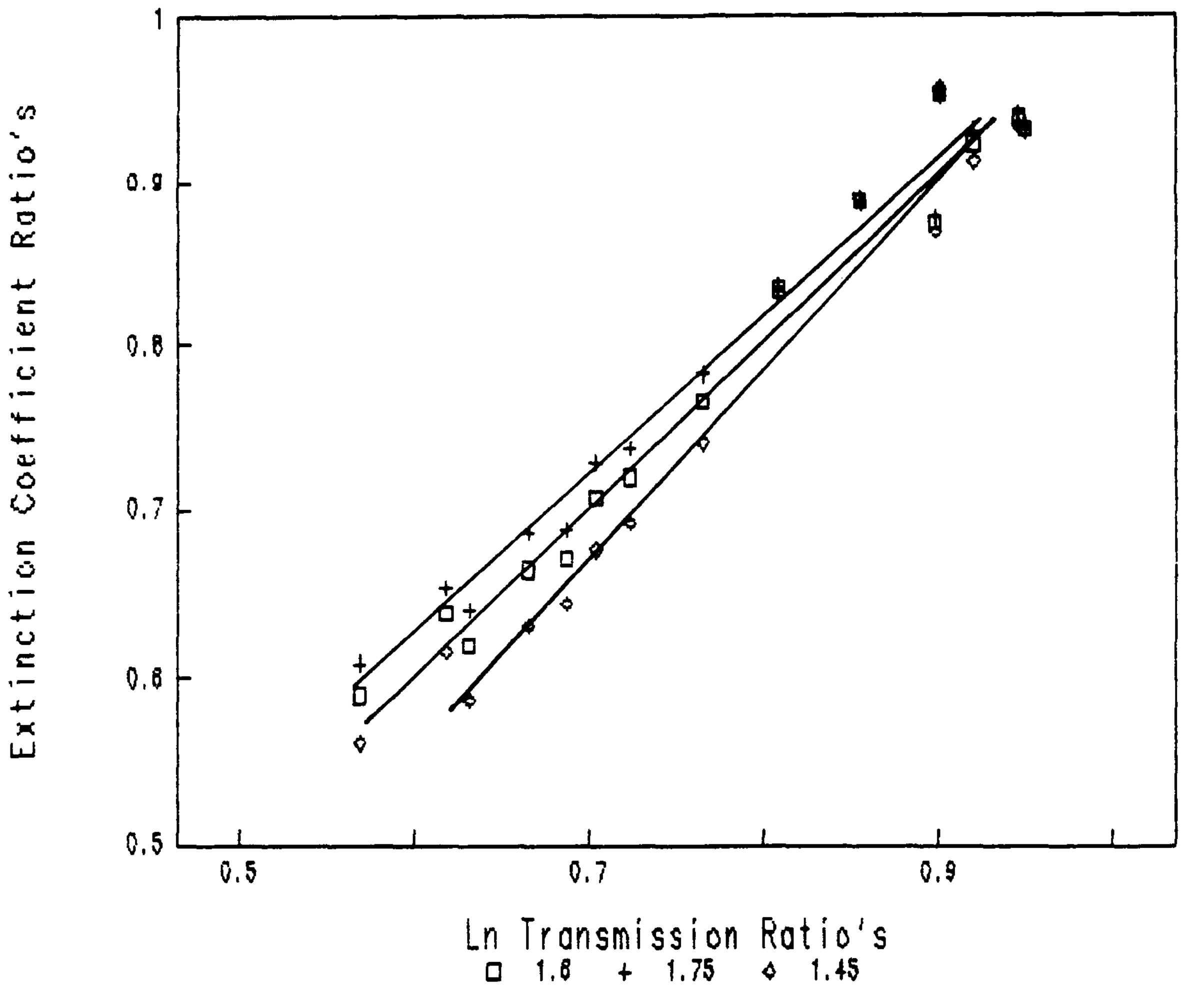


Figure 17.
Results of Perturbation of sigma about 1.6,Run 4

TABLE 3. TEST RESULTS

Test	D_{32}	σ	n	R^2	X-Coef
1	$.33\pm.02\mu$	$1.40\pm.10$	$1.63\pm.02$	.99381	.999540
2	$.21\pm.02\mu$	$1.47\pm.05$	$1.63\pm.06$	.98659	1.00479
3	$.33\pm.02\mu$	$1.60\pm.20$	$1.67\pm.03$	.99676	.995403
4	$.33\pm.02\mu$	$1.60\pm.15$	$1.61\pm.06$	.97354	1.00699
aver uncertainty	$.30\pm.02\mu$	$1.52\pm.12$	$1.64\pm.04$		

C. EFFECTS OF TEST CONDITIONS

For the 16% AL propellant, the change in chamber pressure and degree of over-expansion did not have a profound effect on the optical properties. The index of refraction remained the same, and the change in the standard deviation of the log-normal distribution was within the measurement uncertainty. The Sauter mean diameter decreased in run 2; however, the measurement was made further aft in the plume. D_{32} can change rapidly with plume position [Ref. 14].

Significantly different pressures and expansion ratios had little effect on the properties when using the 4.69% AL. The 16% AL propellant contained a small amount of iron oxide as a burn rate catalyst and used an HTPB binder. The 4.69% AL propellant had no iron oxide and used a GAP binder. With these significant differences, the value of the index of refraction remained at

approximately 1.64, essentially the same as measured by Kim [Ref 9]. This result indicates that the small particles that are rapidly cooled in the nozzle flow are probably γ-Al_2O_3 as observed by other investigators [Ref. 15,16,17]. α-Al_2O_3 has a significantly higher index of refraction.

VI. CONCLUSIONS AND RECOMMENDATIONS

The increase in the number of wavelengths (5 to 6) utilized by the multiple wavelength transmittance apparatus provided more ln-transmittance ratios and increased confidence in the measured parameters obtained by least-squares fitting of the data. The increased A/D rate (33KHz to 500KHz) resulted in the ability to obtain more sweeps (32 vs 8) in significantly less time(70ms vs 250ms). This resulted in two benefits. First, time variations in motor operating conditions had much less effect. Second, more data were obtained for averaging, thereby reducing the effects of the elimination of obviously bad data (due to large particles being present during one sweep, etc.). The new computer code also eliminated the need for hand selection of the peak voltages from the diode array, significantly reducing data reduction time. These modifications did not improve the reported accuracy for determining d_{32} and σ [Ref. 9], but did significantly improve the accuracy for determining the index of refraction (8% to 3%). The average values of d_{32}, n, and σ obtained for the two aluminized propellants were $d_{32}=.30\pm.02\mu$, $n = 1.64\pm.04$ and $\sigma = 1.52\pm.12$.

The results of this investigation, together with that of Ref.9, indicate that the small aluminum oxide particles (that dominate the outer plume regions) are γ-Al_2O_3, independent of propellant composition, motor operating conditions and nozzle

geometry. In addition, the good correlation of the data indicated that the small particles can be adequately represented by a monomodal, log-normal distribution.

Subsequent work should consider further modification of the Fortran code used the generate the Mie extinction coefficients. Currently the code generates the extinction coefficient ratios and d_{32} for three wavelengths. Increasing the number of wavelengths to six, and adding a regression function to automatically determine the best correlation between the measured and calculated results, would shorten data reduction time and increase the overall accuracy.

APPENDIX A - SYSTEM UPGRADES

The upgrades to the system used by Kim [Ref. 9], included increasing the speed of A/D conversion from 33khz to 500khz. This involved replacing the HP69751A A/D card, with the HP69759A A/D card, and adjusting the HP69736A Timer/Pacer card accordingly. Additionally, the HP69790B memory cards were replaced with a HP69791A High Speed Memory card, and four HP69792A Memory Expansion cards. This exchange increased the system storage capacity from less than 14 thousand words to over 850 thousand words of high speed memory. In essence, the new system permitted the collection of sixty times as much data in one fifth the time.

The upgrade in computer hardware also necessitated updating the software programs used to control data collection, storage, and reduction. The original system stored data to one of two 5 1/4 floppy drives, up to the capacity of the diskettes. The increased storage capacity of the memory cards necessitated moving permanent data storage to the hard drive of the HP9836S computer. Currently, the data collection and storage program saves eight binary data files of data at a time. The procedure used for creating and storing the files is readily expandable to 15-20 files of 12 sweeps each. The slow transfer rate of the HP9836S computer, both from the memory cards to the computer, and from the computer to the hard drive, is why only eight files are currently

being created and transferred. An HP interface card is being purchased for a new 486PC. This will permit the full potential of the newer memory system to be realized. The revised data collection program is shown in Appendix C.

APPENDIX B - HEWLETT PACKARD MULTIPROGRAMMER(HP6942A)

1. GENERAL DESCRIPTION

The HP 6942A Multiprogrammer system is a self-contained module that can be used in a wide variety of data capture applications[Ref. 18:p. 1-1,Ref. 19:p. 32]. The Multiprogrammer utilizes a number of I/O cards, and is designed to operate on the HP Interface Bus under control of a desk top computer. The main advantage of the Multiprogrammer and its I/O cards over other data acquisition systems is that its cards can be controlled by dual means [Ref. 18:p. 3-1]. A I/O card can be addressed and controlled by the computer via the back plane edge of the card, or external events can control operation of the card via the edge connectors on the cards. Both means of controlling the I/O cards to collect data have been used. The A/D card and the Timer/Pacer card were both triggered externally by inputs from the photodiode; however the actual data acquisition process was initiated by the computer via inputs from the motor pressure transducer voltage.

The Multiprogrammer can be configured to operate with of up to sixteen I/O cards, depending upon its intended purpose. The current arrangement emphasized the capturing of analog data for conversion and storage to the hard drive of the HP9836S computer.[Ref. 18:p. 2-1]

2. 500 KHZ A/D CARD (HP69759A)

As shipped from the factory, the Analog to Digital conversion card had a nominal ± 10-volt unity-gain input range with 5-millivolt resolution. It can be cycled either internally (via the back plane) or externally (via the edge connector). When it is triggered, the A/D card converts the input voltage into a 12-bit, two's complement binary value within two microseconds. [Ref. 20:p. 1-2] The card has 14 programmable mode functions which include, gain ,trigger, and external lockout control. In this investigation, the card was operated in the ± 1 range, received input voltages from the diode array, and was triggered externally by the timer/pacer card.

3. HIGH SPEED MEMORY(69791A) AND MEMORY EXPANSION CARDS(HP69792A)

The Model 69791A High Speed Memory card consists of two printed circuit boards that are physically attached to each other by four teflon snap connectors. The card has dynamic Random Access Memory(RAM) capable of storing up to 65,536 16-bit words at high speed [Ref. 21:p. 1-1]. The 16-bit data can be written to, or read from, the card by either the computer or an external device. Because the card is capable of simultaneously reading and writing data, the computer can transfer data via the back plane of the Multiprogrammer, while external devices transfer data via the edge connector.

The Model 69792A Memory Expansion card is electrically connected to the HP 69791A via a chaining cable. Each Memory Expansion card that is added to the Memory Card System increases

the number of 16-bit words that can be stored by 196,608 [Ref. 21:p. 1-1]. Up to five expansion cards can be used with one HP 69791A for a storage capacity of 1,048,576 words. The present configuration uses four expansion cards, for a memory capacity of 851,968 words. The Memory Card System has two basic modes of operation: FIFO (First In/First Out) mode and Recirculate mode. In the current setup the Memory Card System was configured in the FIFO mode, and acted as a data buffer. Converted voltages from the A/D card were stored in the Memory Card System before and during the actual rocket motor firing, and later transferred to the hard drive of the HP9836S computer.

4. TIMER/PACER CARD(HP69736A)

The Model HP 69736A Timer/Pacer card is a square wave pulse generator that can generate output pulses from 1 μsec to 18.2 hrs in duration [Ref. 22:p. 1-1]. The card operates in either the one-shot mode (single output pulse) or the recirculate mode (continuous train of output pulses). In the present configuration the Timer/Pacer was operated in the recirculate mode and was triggered externally by the blanking pulse of the diode array. This synchronized the card pulse train with the first sweeps of the diode array, which in turn controlled the conversion rate of data by the A/D card.

APPENDIX C - DATA ACQUISITION PROGRAM

```
20   !########## ACQUIRES MULTIPLE SCANS OF BOTH DIODE ARRAYS ################
30   !##########          AND STORES THEM ON DISK            ################
40   !##########  BERT HANSEN, KEN GRAHAM,KELLY HARRIS 1984   ################
41   !#######################################################################
50   !##########  REVISED FOR USE WITH 500KHZ A/D AND STORAGE ################
51   !##########        ON HARD DRIVE BY JOHN VAUGHN 1992     ################
71   DIM C(1:8192),D(1:8192),Z(1:8192)
120  LOCAL LOCKOUT 7          ! DISABLES FRONT PANELS OF DATA ACQUISITION SYSTEM
130  REMOTE 709
140  OUTPUT 709;"AR"                               ! ANALOG RESET OPENS ALL CHANNELS
160  REMOTE 722                                    !REMOTE IS A LISTEN COMMAND
170  OUTPUT 722;"HSM002SO1D1L1Z0F1FL0R11STN.01STIT30"        !PROGRAM VOLTMETER
180   ! H homes the DVM .(like RESET)  SM002 sets the service request mask to
190   ! tell the computer that a measurement was taken and is ready to be read.
200   ! page 3-20 of DVM MANUAL. SO1 means that no reading wil; be taken until
210   ! the computer receives the one just made(page 3-26). D1 means DISPLAY ON.
220   ! L1 means load the following instructions. Z0 means AUTO ZERO OFF for
230   ! faster but less precise readings. F1 means DC VOLTS measurement.
240   ! FL0 means FILTER OFF for faster readings. R1 is AUTO RANGING. 1STN means
250   ! 1 reading will be taken for each trigger. .01STI---.01powerline cycles
260   ! will be the integration time. T3 is a single trigger. Q means END
270  GOSUB Initiate
410  PRINT USING "@"
420  PRINT " DATA WILL BE STORED ON HARD DRIVE WITH FOLLOWING FILE NAMES:"
430  PRINT USING "///"
440  PRINT "   NO PARTICLES ---- A..D"
450  PRINT "   PARTICLES ------- E..H"
451  OUTPUT 709;"DC11,2"     ! OPEN SHUTTER
460  PRINT USING "//"
470  PRINT "                 IS THIS A CALIBRATION ?   ENTER ' Y ' IF YES "
480  PRINT "                              ANYTHING  ELSE  IF  ACTUAL  RUN"
490  INPUT R$
540  IF R$="Y" THEN 734
550  PRINT USING "@"
560  INPUT "ENTER THE THE TRIGGER VOLTAGE",Vt
590  OUTPUT 709;"AC20"                              !CHANNEL FOR CHAMBER PRESSURE
600  WAIT .3                             ! THIS WAIT IS TO LET VOLTAGES SETTLE DOWN
610  V1=0
620  CLEAR 722            ! THIS DOES NOT ALTER THE INSTRUCTIONS FOR THE VOLTMETER
630                      !IT CLEARS ANY NUMBERS IN THE DISPLAY OR OUTPUT REGISTERS
640  FOR I=1 TO 10
650    OUTPUT 722;"X1"                            !TRIGGER VOLTMETER
660    GOSUB Reading                              !READ VOLTMETER
670    V1=V1+V
680  NEXT I
690  Vz=V1/10            ! THIS AVERAGES READINGS TO GET A ZERO PRESSURE VALUE
700  PRINT USING " 40A,D.6D";"                 ZERO PRESSURE VOLTAGE IS      ",Vz
710  PRINT ""
731  PRINT "   DATA ACQUISITION BEGINS WHEN VOLTAGE EXCEEDS  ",Vt
732  WAIT 4
734  Part=0
735  PRINT USING "@"
743  PRINT "TAKING NO PARTICLE DATA"
744  !WAIT 3
750  GOSUB Multiprog                      ! TAKES NO-PARTICLE DATA
760  GOSUB Purge
761  GOSUB Storedata
770  IF R$="Y" THEN 950                   ! IF CALIBRATION THEN SKIP SOME LINES
780  PRINT USING "/"
790  PRINT "                          BE SURE NITROGEN IS ON"
800  PRINT "BE SURE VISICORDER IS SET UP TO RUN ON PROPER SCALE WITH LAMP ON."
801  WAIT 3
810  PRINT USING "/"
820  !DISP "                          STANDING BY FOR IGNITION"
830  PRINT "                          STANDING BY FOR IGNITION"
831  WAIT 3
840  BEEP 2000,.1
```

COPY AVAILABLE TO DTIC DOES NOT PERMIT FULLY LEGIBLE REPRODUCTION

```
[illegible] CLEAR [illegible]
[illegible] WAIT 3
[illegible] OUTPUT [illegible]                              TRIGGER VOLTMETER
[illegible] GOSUB Reading
900  R9=ABS(V-V7)                          !THIS IS VOLTAGE CORRESPONDING TO PRESSURE
910  PRINT R9
911  WAIT 3
920  IF R9<V THEN GOTO 880   IF PRESSURE IS BELOW THRESHOLD PRESSURE--REPEAT
950  IF R$<>"Y" THEN 1011                       !IF ACTUAL RUN THEN SKIP SOME LINES
960  !                   FOR CALIBRATIONS INTRODUCE PARTICLES AND THEN CONTINUE
970  PRINT CHR$(12)
930  PRINT USING "/////////"
990  PRINT "                    INTRODUCE PARTICLES THEN PRESS KEY # 9 TO TAKE DATA"
1000 ON KEY 9 LABEL "  TAKE DATA" GOTO 1011
1010 Standby:GOTO Standby
1011  Part=1
1012  PRINT USING "///"
1014  PRINT "TAKING PARTICLE DATA"
1015  WAIT .4
1020  GOSUB Multiprog                                       ! TAKE PARTICLE DATA
1040                                                    !PARTICLE DATA FILE NAME
1057  GOSUB Storedata
1081  OUTPUT 727;"AR"                              !A/D is in slot# 1
1082  LOCAL 7                                      !Mem Card        2,3
1090  GOTO 3900                                    !Timer/pacer     9
1100 Multiprog:                                      !Mem Exp Cards   4,5,6,7
1101  Cdelay=0
1103  OUTPUT 727;"DO1,2"
1105  OUTPUT 723;"WF,8,2,1T"                   !SETS RECIRCULATE MODE
1106  OUTPUT 723;"WF,8,10"                    !GENERATES 50KHZ PULSE TRAIN
1107  OUTPUT 723;"CY,8T"                     !ACTIVATES CARD
1117  Cdelay=Cdelay+1
1127  IF Cdelay<5 THEN
1137    GOSUB Initiate
1147    GOTO 1105
1157  END IF
1305  IF Part=0 THEN
1309    PRINT USING "///"
1311    PRINT "NO PARTICLE DATA IS STORED ON MEMORY CARDS "
1312    WAIT 3
1314  END IF
1320  IF Part=0 THEN GOTO 1590
1330  PRINT USING "///"
1404  PRINT "PARTICLE DATA IS STORED ON MEMORY CARDS "
1590  RETURN
1600 Storedata:!
1601  PRINT USING "///"
1602  PRINT "DATA IS BEING TRANSFERED FROM THE CARDS TO THE COMPUTER"
1603  PRINT USING "/"
1605  PRINT "WHEN THE TRANSFER IS COMPLETE THE FIRST 5 ENTREES OF EACH FILE"
1606  PRINT "                         WILL BE DISPLAYED"
1607  FOR J=65 TO 72
1609    IF Part=0 THEN
1610      OUTPUT 723;"WF2,3,76T"                     !FIFO-IN WITH LOCKOUT
1611      OUTPUT 723;"MI";2;8192;"T"
1612      ENTER 72305;Z(*)
1614      PRINT "NEGATIVE VOLTAGE LOOP"
1615      FOR I=1 TO 8192
1616        IF Z(I)<32000 THEN
1617          C(I)=Z(I)*.0005
1618          GOTO 1630
1619        END IF
1621        C(I)=(65535-Z(I))*.0005
1630      NEXT I
1782      Lucky$=CHR$(J)
1783      ASSIGN @Path2 TO Lucky$
1784      OUTPUT @Path2;C(*)
```

```
1791       Lucky$=CHR$(J)
1792       ASSIGN @Path2 TO Lucky$
1793       PRINT "BOAT ";CHR$(J)
1794       FOR N=1 TO 5
1795         ENTER @Path2;M
1796         PRINT M
1797       NEXT N
1798       IF Part=0 AND J<68 THEN GOTO 1806
1799       IF Part=1 THEN GOTO 1805
1301       GOTO 1807
1802     ELSE
1803       IF J<=68 THEN GOTO 1836
1804       GOTO 1610
1805     END IF
1806   NEXT J
1807   WAIT 1
1803   OUTPUT 723;"WF2.3,56T"                         !FIFO-IN WITHOUT LOCKOUT
1809   RETURN
1810 Reading:!
1811   ENTER 722;V                                    ! READS VOLTMETER
1830   RETURN
1840 Initiate:!
1880   OUTPUT 723;"WF,2.3,255,2.3,56,T"!Initialize the Mode register
1881   OUTPUT 723;"WF,2.1,30,2.2,0,T"!Set reference 2(low order word)
1882   OUTPUT 723;"WF,2.1,31,2.2,0,T"!Set reference 2(high order word)
1883   OUTPUT 723;"WF,2.1,26,2.2,177777,T"!Set reference 1(low order word)
1884   OUTPUT 723;"WF,2.1,27,2.2,17,T"!Set reference 1(high order word)
1885   OUTPUT 723;"WF,2.1,22,2.2,0,T"!Reset Read Pointer(low order word)
1886   OUTPUT 723;"WF,2.1,23,2.2,0,T"!Reset Read Pointer(high order word)
1887   OUTPUT 723;"WF,2.1,20,2.2,0,T"!Reset the Difference counter(low order word
)
1888   OUTPUT 723;"WF,2.1,21,2.2,0,T"!Reset the Difference counter(high order
word)
1889   OUTPUT 723;"WF,2.1,24,2.2,0,T"!Reset the Write pointer(low order word)
1890   OUTPUT 723;"WF,2.1,25,2.2,0,T"!Reset the WFrite pointer(high order word)
1891   OUTPUT 723;"CC,2,1T"!Send a clear card instruction
1892   PRINT USING "3/"
1393   OUTPUT 723;"WF,2.3,56T"        !SET MEMORY CARD TO FIFO-IN MODE
1394   OUTPUT 723;"CY";2;"T"          !ACTIVATE CARD
1875   OUTPUT 723;"WF1.1,11,1.2,0T"   !DISABLE MUX(Need to enable mux if ever
                                      !switch back to 1417A connector cable)
1895   OUTPUT 723;"WF1.1,12,1.2,0T"   !DSBL OUTPUT FALSE
1897   OUTPUT 723;"WF1.1,13,1.2,0T"   !ENBL EEN FALSE
1858   OUTPUT 723;"WF1.3,0T"          !RESET A/D MODE BITS
1899   OUTPUT 723;"WF1.1,2,1.2,1T"    !SET EXTERNAL TRIGGER
1900   OUTPUT 723;"WF1.1,1,1.2,0T"    !DISABLE INTERNAL TRIGGER
1701   OUTPUT 723;"WF1.1,3,1.2,0T"    !TRIGGER POLARITY SELECT INPUT DISABLED
1902   OUTPUT 723;"WF1.1,4,1.2,1T"    !EXT LOGIC SENSE ACTIVE HIGH
1763   OUTPUT 723;"WF1.1,5,1.2,1,T"   !EXTERNAL LOCKOUT-INPUT ENABLED
1704   OUTPUT 723;"WF1.1,7,1.2,0T"    !MULTIPLE EXTERNAL TRIGGER RESPONSE
1705   OUTPUT 723;"WF1.1,20,1.2,1T"   !PROGRAM GAIN X10(FOR LSB OF .0035)
1907   OUTPUT 723;"CC0T"              !CLEAR TIMER/PACER CARD
1913   RETURN
1916 Purge: !
1920   FOR I=65 TO 66
1930     Lucky$=CHR$(I)
1940     PURGE Lucky$
1950   NEXT I
1960   FOR I=65 TO 66
1970     Lucky$=CHR$(I)
1980     CREATE BDAT Lucky$,8192,16
1981     ASSIGN @Path2 TO Lucky$
1982   NEXT I
1983   PRINT USING "///"
1985   PRINT "HAD TO PURGE AND CREATE BDAT FILES"
2000   RETURN
3000   END
```

LIST OF REFERENCES

1. Netzer, D. W., *Tactical Missile Propulsion-Design and Applications*, Submitted to Particle Science and Technology, 1992, pp 1-3.

2. Laredo, D., Netzer, D., *Application of Optical Diagnostics to Particle Measurements in Solid Propellant Rocket Motors and Exhaust Plumes*, Unpublished Notes, Naval Postgraduate School, 1992,pp 1-3.

3. Few, J., Hornkohl, J., *Measurement and Prediction of Jet Engine Particulate Effluents*, University of Tennessee Space Institute Center for Laser Application, Report No. NAPC-PE-195C, February 1990,pp 1-10.

4. Few, J., Lewis,J., Hornkohl, J., *Optical Measurements of Turbine Engine Exhaust Particulates*, University of Tennessee Space Institute Center for Laser Application, Report No. NAPC-PE-221C, July 1991,pp 1-8.

5. Dash, S.M., "Analysis of Exhaust Plumes", *Tactical Missile Aerodynamics*, AIAA Progress in Astronautics and Aeronautics, vol 104, pp. 778-851.

6. Nelson, H.F., "Influence of Particulates on Infrared Emission from Tactical Rocket Exhausts", *J. Spacecraft*, Vol 21, No. 5, Sept-Oct 1984, pp 425-432.

7. Cashdollar, K. L., Lee, C. K. and Singer, J. M., *Three-Wavelength Light Transmission Technique to Measure Smoke Particle Size Concentration*, Applied Optics, Vol. 18, No. 11 June 1979,pp. 1763-1769.

8. Powell, E.A. and Zinn, B.T., "In situ Measurements of the Complex Refractive Index of Combustion Generated Particulates", *Combustion Diagnostics by Nonintrusive Methods*, AIAA Progress in Astronautics and Aeronautics, Vol. 92, 1984, pp 238-251.

9. Kim, H., *Multiple-Wavelength Transmission Measurements in Rocket Motor Plumes*, Master's Thesis, Naval Postgraduate School, Monterey, California, September 1991,pp 3-8,40.

10. Oriel Corp., *Light Sources*, Oriel Catalog, Volume II, Stratford, CT.

11. EG & G Reticon, *Spectral Response of Reticon Linear Photodiode Arrays*, Application Notes, No. 121, Sunnyvale, California.

12. Harris, R, *An Apparatus for Sizing Particulate Matter in Solid Rocket Motors*, Master's Thesis, Naval Postgraduate School, June 1984, p. 41.

13. Nowell, J., Missile Total and Subsection Weight and Size Estimation Equations, Master's Thesis, Naval Postgraduate School, Monterey, California, June 1992.

14. Hwang, C.J. and Chang, G.C., "Numerical Study of Gas-Particle Flow in a Solid Rocket Nozzle", *AIAA J.* Vol. 26, No.6, June 1988, pp. 682-689.

15. Strand, L.D., Bowyer, J.M., Varsi, G., Lane, E.G. and Gauldin, R., "Characterization of Particulates in the Exhaust Plume of Large Solid-Propellant Rockets", *J. Spacecraft*, Vol. 18,No.4, July-Aug 1981, pp. 297-305.

16. Dill, K.M., Reed, R.A., Calia, V.S. and Schulz, R.J., "Analysis of Crystalline Phase Aluminum Oxide Particles in Solid Propellant Exhaust", *J. Propulsion,* Sept-Oct. 1990, pp 668-671.

17. Dobbins, R.A. and Strand, L.P., "A Comparison of Two Methods of Measuring Particle Size of Al_2O_3 Produced by a Small Rocket Motor", *AIAA J.*, Vol. 8, No. 9, Sept. 1970, pp. 1544-1550.

18. *Hewlett Packard Application Note 316-5, Data Capture with the 6942A/6944A Multiprogrammers*, HP Part Number 5952-4116, December 1984.

19. Wendland,R., *Upgrade and Extension of the Data Acquisition System for Propulsion and Gas Dynamic Laboratories*, Master's Thesis, Naval Postgraduate School, Monterey, California, June 1992.

20. *Hewlett Packard 500 Kilohertz Analog-to-Digital Converter Card Model 69759A*, HP Part Number 69759-90001, June 1984.

21. *Hewlett Packard High Speed Memory Card Model 69791A and Memory Expansion Card Model 69792*, HP Part Number 5950-1980, March 1984.

22. *Hewlett Packard Timer/Pacer Card Model 69736A*, HP Part Number 69736-90003, April 1983.

INITIAL DISTRIBUTION LIST

		NO. Copies
1.	Defence Technical Information Center Cameron Station Arlington, Virginia 22304-6145	2
2.	Library, Code 52 Naval Postgraduate School Monterey, California 93943-5002	2
3.	Department Chairman, Code AA Department of Aeronautics Naval Postgraduate School Monterey, California 93943-5000	1
4.	Professor D.W. Netzer, Code AA/Nt Department of Aeronautics Naval Postgraduate School Monterey, California 93943-5000	2
5.	Professor R.P. Shreeve, Code AA/Sf Department of Aeronautics Naval Postgraduate School Monterey, California 93943-5000	2
6.	CPT J.K. Vaughn 167 Lawrence St. Uniondale, NY 11553	5